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Supercritical CO₂ core flooding and imbibition in Berea sandstone – CT imaging and numerical simulation

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Abstract

This paper reports a numerical simulation study of a full CO₂ core flooding and imbibition cycle on a Berea sandstone core (measured 14.45 cm long and 3.67 cm in diameter). During the test, supercritical CO₂ (at 10 MPa and 40°C) and CO₂-saturated brine was injected into one end of the horizontal core and a X-ray CT scanner (with a resolution of 0.35mm x 0.35mm) was employed to monitor and record changes in the fluid saturations, which enabled 3D mapping of the saturation profiles throughout the core during the course of core flooding test. From the digital CT saturation data, mean saturation profiles along the core length were plotted with time. A 1D model of the core was constructed to simulate the core flooding test and attempt was made to history match core test results, particularly the evolution of the mean CO₂ saturation profiles during CO₂ injection. Curve-fitting of the centrifugal air-water capillary pressure data (drainage) for the Berea core showed that the core test data could be adequately described by the Van Genuchten equation. The matched set of parameters (S_{lr} , P_0 , m) were 0.09, 20 KPa, 0.425 respectively. In the absence of the relative permeability for the Berea core, it was decided to use the parameters obtained from matching the air-water capillary pressure data as a first approximation for the CO₂-brine system in the model.

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1. Introduction

Three storage mechanisms in aquifers have been identified, in increasing order of time scale, hydrodynamic (or residual CO₂ saturation) trapping, solution trapping (dissolution in the formation water), and mineral trapping through geochemical reactions with formation fluids and rocks. A proper understanding of these mechanisms for a given storage site is important in order to improve public confidence in the long-term subsurface storage of CO₂. In an effort to determine CO₂ residual saturation and gain a better understanding of this CO₂ trapping mechanism in sandstone aquifers, supercritical CO₂ core flooding and follow-on imbibition tests on Tako and Berea sandstones have recently been carried out by one of the authors [1]. A total of 7 tests (involving one Tako and six Berea cores) were reported, including two where X-ray CT scanning was employed to enable 3D mapping of the saturation profiles during the course of CO₂ flooding and imbibition. A detailed numerical modelling study of the CO₂ core flooding and imbibition tests on the Tako core, which has a heterogeneous porosity distribution, has been reported elsewhere [2]. This paper reports a follow-up study on one of the Berea cores, which are relatively homogeneous, with CT imaging. A 1D model of the core was constructed to simulate the CO₂ injection and imbibition processes in the sandstone core and in particular to history match the time evolution of the CO₂ saturation profiles.

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2. CO₂ core flooding and imbibition tests with simultaneous CT scanning

A schematic diagram of the core flood system, which features a Toshiba Aquilion 16 CT scanner and an aluminium core holder can be found in Shi et al. [2]. The core holder is horizontally placed to fit into the CT scanner. During a drainage/imbibition flooding test, the temperature, as well as the pressure, of the system is maintained. Supercritical CO₂/CO₂ saturated brine is injected through the right end of the core. Viton 70 Durometer (temco) is used for sealing the sandstone core to prevent the invasion of hydrostatic pressure medium (water).

The Berea sandstone core of interest here measured 3.67 cm in diameter and 14.45 cm long. It had a porosity of 0.187, giving rise to a pore volume (PV) of 28.45 cm³, and an air permeability of 330 mD (1 mD = 10⁻¹⁵ m²) at a confining pressure of 13.79 MPa. Pore size distribution analysis by mercury injection revealed that the pore volume mainly resided in the pores with radius ~ 10 microns (Figure 1). The average pore radius of the sample was 6.72 microns.

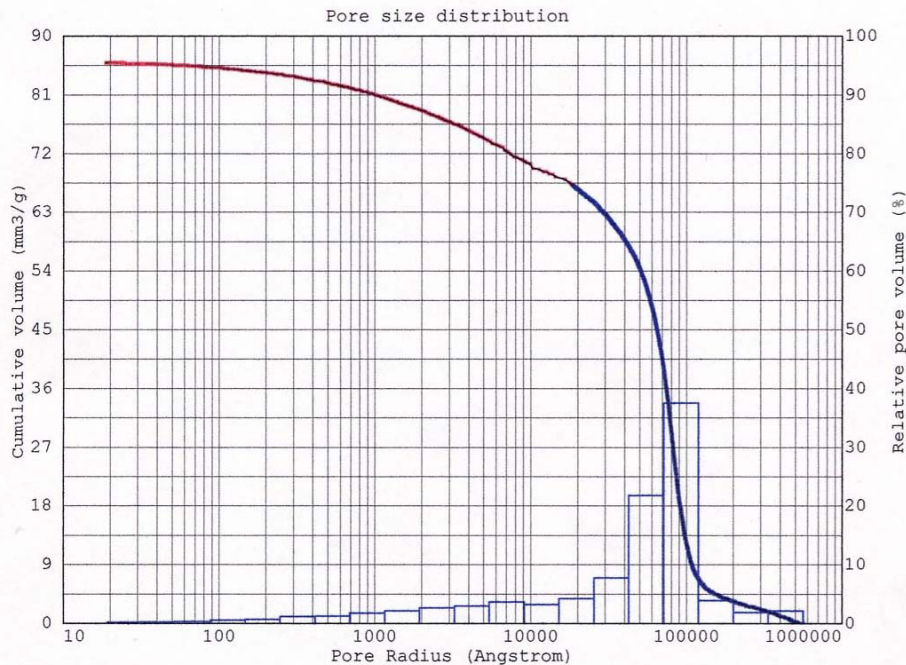


Figure 1. Berea sandstone core pore size distribution (1 Angstrom = 10⁻¹⁰ m).

To map out the porosity distribution of the core, fine resolution (0.35mm x 0.35mm) CT images of the core cross sections were taken at a regular interval of about 2 mm along the core length (thus giving rise to a total of 70 images), under both dry and water-saturated conditions. Further details of the experimental procedure used can be found in Shi et al. [2]. Porosity is calculated using the obtained CT values (CT_{r-air} and CT_{r-w}) as well as those for air and water (CT_{air} and CT_w), $\phi = (CT_{r-w} - CT_{r-air}) / (CT_w - CT_{air})$. CT scanning was also performed over the longitudinal section of the core. CT scan imaging showed that the core had a relatively homogeneous porosity distribution (Figure 2). There were close to 100 x 100 porosity data on each image in Figure 2a.

Prior to CO₂ injection, the core was saturated with brine (3wt% NaCl) doped with 5wt% NaI to enhance the contrast in CT images. It is noted that introducing NaI in the system could potentially result in an increase in the capillary pressure of the non-wetting phase during the flooding test [2].

During the flooding test, supercritical CO₂ (at 10 MPa and 40°C) totalling 30.4 PV was injected into the horizontally oriented core. The injection rate was increased from an initial 0.1 cc/min to 4.5 cc/min in several steps. By the end of the flooding test, the average CO₂ saturation in the core reached approximately 31%. The follow-on imbibition cycle saw the injection of 29.7 PV CO₂ saturated brine at a constant rate of 1 cc/min. During both the CO₂ injection and imbibition tests, changes in the phase saturation distribution within the core were monitored by CT scanning. Fine resolution (0.35mm x 0.35mm) images of a thin slice were taken at an interval of about 2 mm along the core length. CT scanning was also performed over the longitudinal section of the core. Figures 3a and 4a illustrate the snap shot CT images of phase saturation at different stages of the CO₂ flooding and imbibition tests, displaying graphically the migration of the injected CO₂ and brine with time.

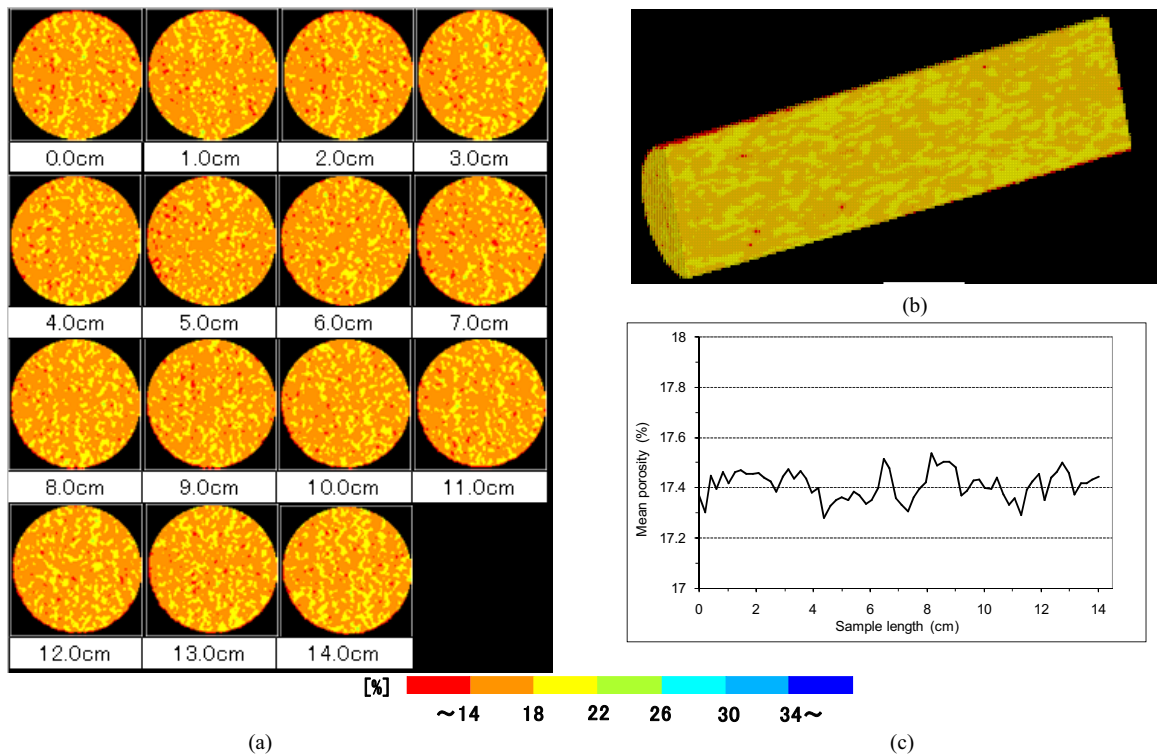


Figure 2. CT images showing porosity distribution within (a) cross-sections at 1-cm interval over the core length; (b) longitudinal cross-section; (c) computed mean porosity at the imaged cross-sections from the digital CT data.

2.1. Porosity and CO_2 saturation profiles

As a first step of data analysis, mean porosity profile along the core length was generated from the CT data by averaging the 100 x 100 CT porosity values at each of the 70 cross-sections and plotting them against its spatial position along the core. The resulting porosity profile is shown in Figure 2c. The mean porosity is seen to vary along the core length, within a narrow range between 0.173 and 0.175, slightly lower than the measured core porosity of 0.187.

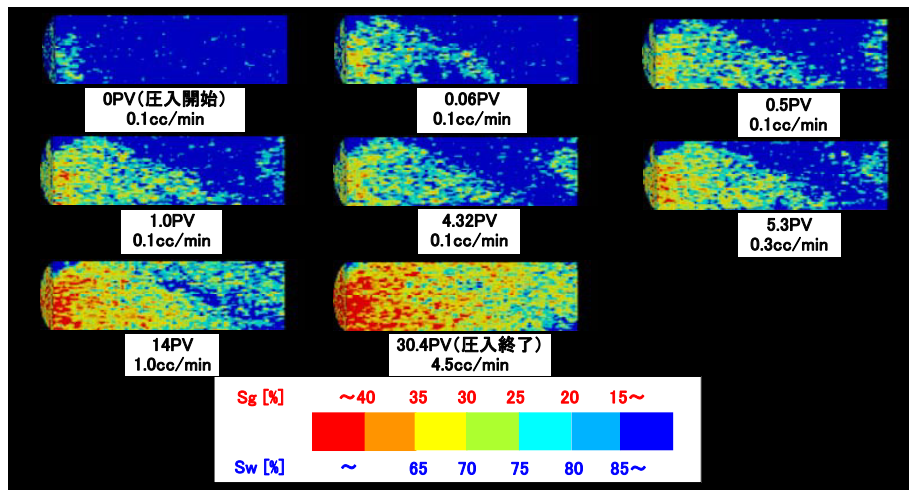
Similarly, mean saturation profiles along the core length could be obtained from the digital CT saturation data. The resulting CO_2 saturation profiles for both drainage and imbibition are plotted in Figures 3b and 4b respectively. The following observations can be made:

CO_2 flooding (Figure 3b)

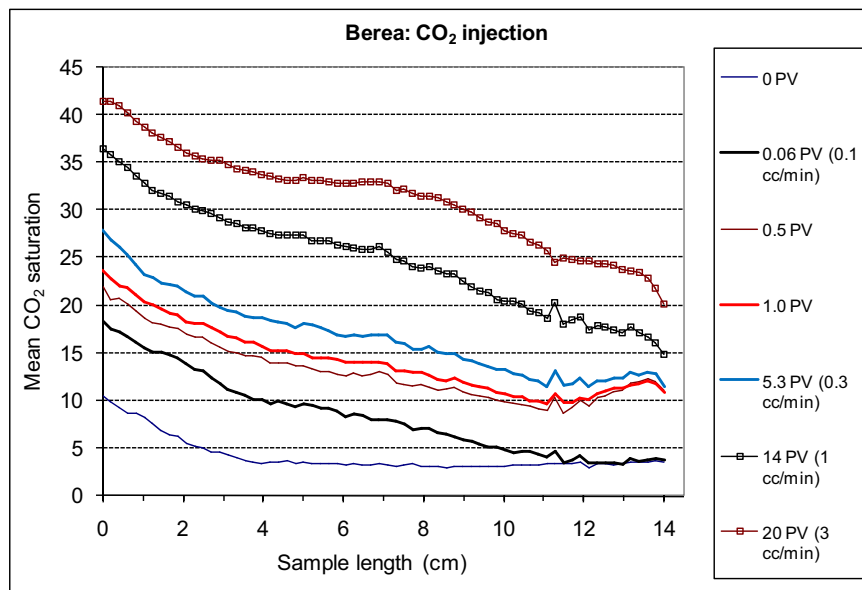
- The CT saturation data indicated that the sandstone core was not fully saturated with water at the start of CO_2 injection (0 PV). Rather it appeared to contain a residual (air) gas phase with an average saturation of roughly 4.2%. It is possible that the apparent residual gas saturation may be partly due to the unconnected pores inaccessible to the brine.
- CO_2 breakthrough was observed shortly after 0.06 pore volume (PV) of CO_2 was injected.
- At an injection rate of 0.1 cm/min, the mean level of CO_2 saturation in the core rose to 0.143 after the injection of 1 PV CO_2 (Strictly speaking, the gas phase may also contain part of the initially trapped residual gas).
- Staged rise in the CO_2 injection rate, first to 0.3 cc/min, then to 1.0 and 3.0 cc/min, resulted in an incremental increase in the CO_2 saturation, reaching ~ 0.313 after 20 PV of CO_2 was injected.

Imbibition (Figure 4b)

- Brine breakthrough occurred before 0.2 PV of brine was injected.
- The core CO_2 saturation was reduced from an initial value of ~ 0.313 to ~ 0.21 after 1.0 PV of brine was injected. It then remained practically unchanged with further brine injection up to 8.0 PV.
- Upon continued brine injection, the displacement became dominated by fingering (Figure 4a). The CO_2 concentration was steadily reduced to below 0.09 (not shown).



(a)



(b)

Figure 3. (a) CT images of phase saturation distribution during CO_2 flooding (drainage) test. Caption underneath each image represents the cumulative injected CO_2 volume (PV) and the spot injection rate; (b) Mean gas saturation profiles computed from the CT data, cross plotted with the porosity.

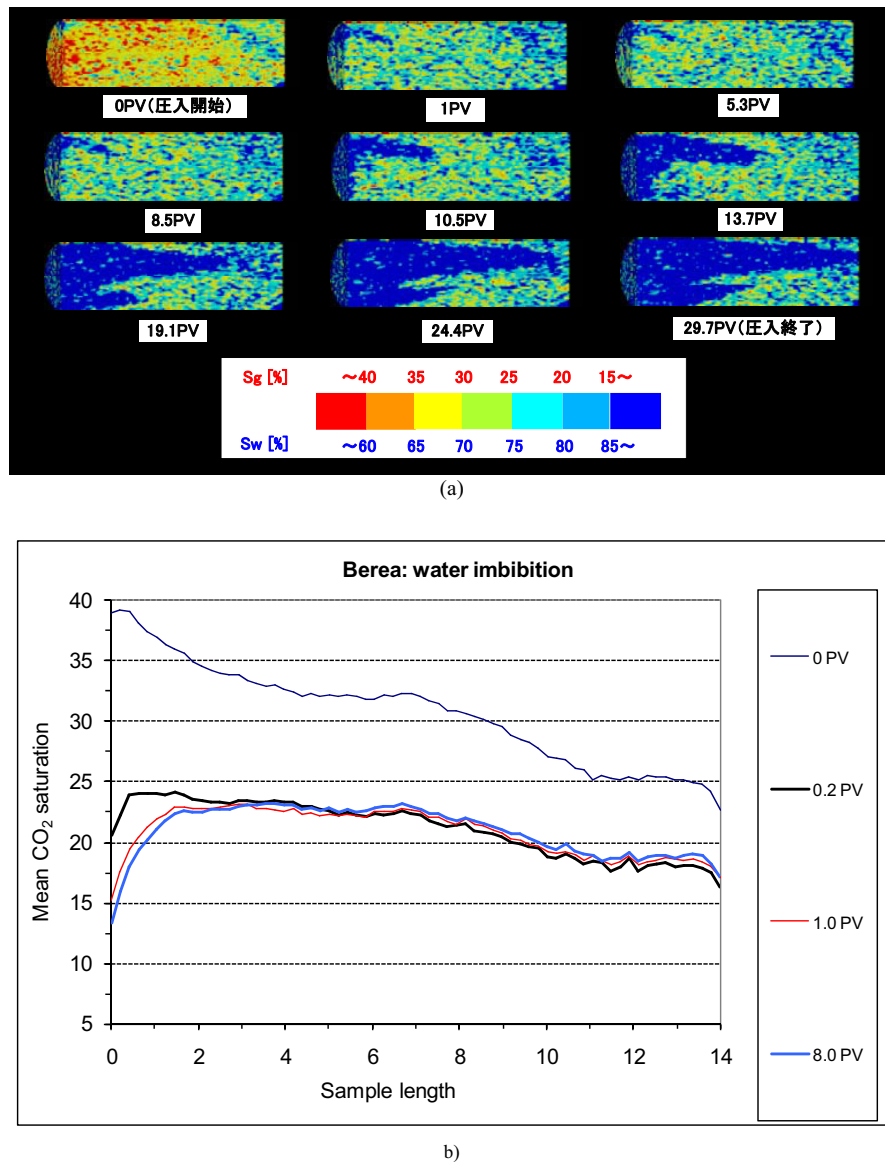


Figure 4. (a) CT images of phase saturation distribution during imbibition test. a) Caption underneath each image represents the cumulative injected CO₂ volume (PV) and the spot injection rate; b) Mean gas saturation profiles computed from the CT data, cross plotted with the porosity.

3. Numerical simulation of the core flooding and imbibition tests

The numerical simulation aimed to gain a better understanding of immiscible displacement of brine by supercritical CO₂ and the subsequent imbibition process in the relatively homogeneous Berea core, through history matching of core tests results, particularly the evolution of the mean CO₂ saturation profiles (Figures 3b and 4b). For simplicity, the supercritical CO₂-brine system was treated as a supercritical CO₂-water two-phase problem. The Imperial College in-house two-phase multi-component coalbed reservoir simulator (METSIM2) has been modified to account for CO₂ storage in aquifers.

A 1D model (24 x 1 x 1) of the core was constructed with varying porosity along the core length reflecting the CT profile (Figure 2c). Permeability-porosity correlations were then used to define the absolute permeability at each gridblock (cell), constrained by an overall permeability of 330 mD, which was the permeability to gas measured at a confining pressure of 13.8 MPa.

The CT images (0 PV curve in Figure 3a) show that the core was not fully saturated with brine at the beginning of the CO₂ injection. For simplicity, it was assumed that the unconnected pore volume in the Berea core could be ignored. Further, the 1D model had an initial gas (CO₂) saturation given by the CT data, and the resident brine (water in the model) was already saturated with supercritical CO₂ prior to injection. As a result CO₂ dissolution in brine/water during the injection test was not considered

during the simulation. Nor were the potential evaporation of the pore water into the CO₂-rich phase and the capillary end effects on the flooding behaviour after CO₂ breakthrough considered.

The model boundary conditions were such that the outlet end was assigned a fixed pressure (10 MPa), while the inlet end was subjected to a CO₂/water injection rate corresponding to the test injection rate.

3.1. CO₂ injection (drainage)

The CO₂-brine relative permeability curves and capillary pressure for the Berea cores were not available. However, (drainage) capillary pressure has been measured using the centrifugal technique for air-water systems. The equations of Van Genuchten [3] and Corey [4], commonly used for two-phase systems in the petroleum industry, were used to describe the wetting-phase relative permeability and capillary pressure, and the non-wetting (CO₂) phase respectively. The equations are listed in Table 1.

Table 1. Relative permeability and capillary pressure functions used in this study.

Relative permeability for gas [4]	Relative permeability for liquid and capillary pressure [3]
$k_{rg} = (1 - S')^2 (1 - S'^2)$	$k_{rl} = \sqrt{S^*} \{1 - (1 - [S^*]^{1/m})^m\}^2$
where $S' = (S_l - S_{lr}) / (1 - S_{lr} - S_{gr})$ S_{lr} : irreducible water saturation S_{gr} : residual gas saturation	$P_c = -P_0 ([S^*]^{-1/m} - 1)^{1-m}$ where $S^* = (S_l - S_{lr}) / (1 - S_{lr})$

As illustrated in Figure 5a, the centrifugal test capillary pressure data for the Berea cores could be adequately described by the Van Genuchten equation. The matched set of parameters (S_{lr} , P_0 , m) are 0.09, 20 KPa, 0.425 respectively. Good match to the air-water capillary pressure data for the Tako core was also obtained [2]. In the absence of the relative permeability and capillary pressure data for the Berea core, it was decided to use the parameters obtained from matching the air-water capillary pressure data as a first approximation for the CO₂-brine system in the model. In addition to the end-point for brine (S_{lr}), S_{gr} is required to compute the CO₂ relative permeability, which was to be determined by history matching the CT CO₂ saturation profiles.

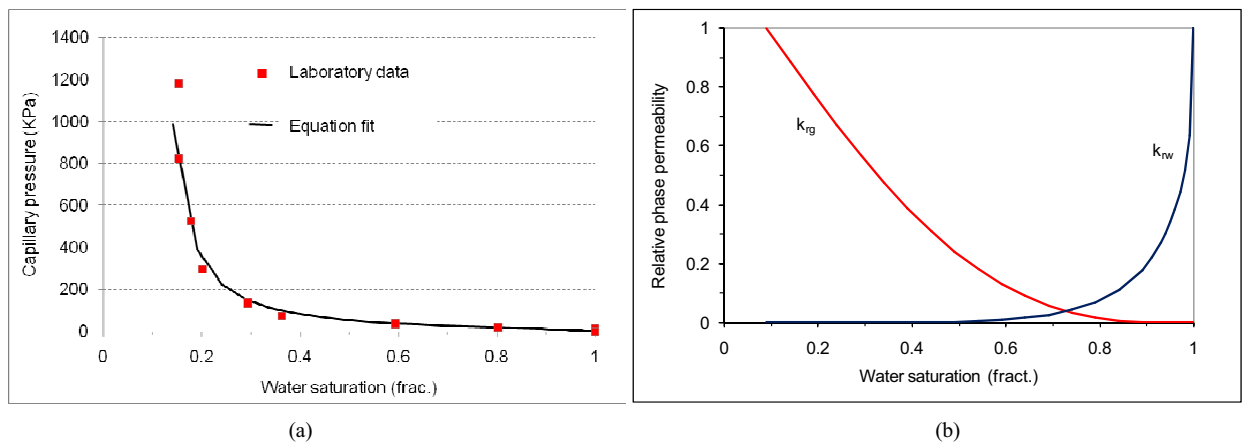
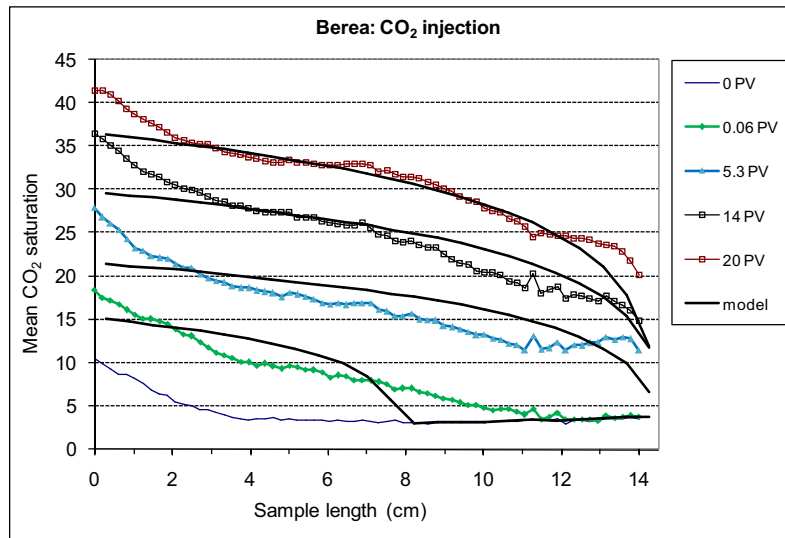


Figure 5. (a) Centrifugal air-water capillary pressure measurements and curve-fit using van Genuchten equation; (b) Relative permeability curves used in the history matching.

It was found that a best overall match to the saturation profiles was obtained with $S_{gr} = 0.025$. The corresponding relatively permeability curves are plotted in Figure 5b. The simulated saturation profiles using the 1D model are compared with the CT profiles in Figure 6. It can be seen that progressively better match to the CT profiles was obtained as the injection rate was increased.

Figure 6. History matching of the mean CO₂ saturation profiles during CO₂ flooding.

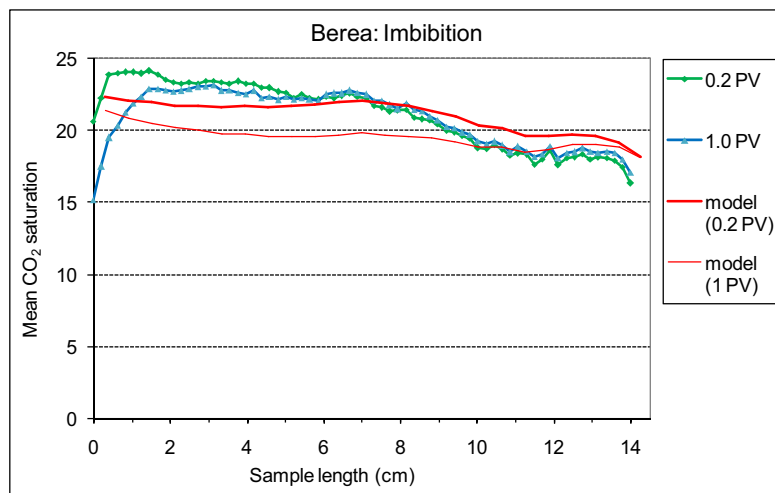
3.2. CO₂ saturated-water injection (imbibition)

Hysteresis behaviour of multi-phase flow in porous medium, particularly in relative permeability and capillary pressure, is due to the difference in the contact angle between the advancing and receding fluid and the solid surface, and the variation of pore throat to pore body ratio and the pore size distribution. Hysteresis in the residual gas (CO₂) saturation, and associated hysteresis in the (non-wetting phase) relative permeability and capillary pressure curves, is of particular interest and relevance here. The trapped gas saturation (S_{gt}) is traditionally described by the Land's constant C , which relates S_{gt} to the initial (prior to the imbibition cycle) gas saturation S_{gi} .

$$C = \frac{1}{S_{gt} - S_{gr}} - \frac{1}{S_{gi} - S_{gr}} \quad (1)$$

The imbibition test yielded a trapped CO₂ saturation of approximately 0.21 for the Berea core, from an initial saturation (S_{gi}) of ~0.31. This gives rise to a Land's constant of 1.9, with $S_{gr} = 0.025$.

For simulation of the imbibition test, relevant scanning curves for the non-wetting phase (CO₂) relative permeability and the capillary pressure are required. These are computed using Killough's [5] method and the relevant equations can be found in the ECLIPSE technical manual (cited in Mo and Akervoll [6]). The simulated CO₂ saturation profiles are compared with the CT data in Figure 7.

Figure 7. Simulated vs. CT mean CO₂ saturation profiles during the imbibitions cycle.

4. Concluding remarks

A 1D model of the Berea core was constructed to simulate the core flooding test and attempt was made to history match the evolution of the mean CO₂ saturation profiles during CO₂ injection. In the absence of the relative permeability for the Berea core, the parameters obtained from matching the air-water capillary pressure data was used as a first approximation for the CO₂-brine system in the model. The matched set of parameters (S_{lr} , P_0 , m) were 0.09, 20 KPa, 0.425 respectively. It was found that a best overall match to the saturation profiles was obtained with $S_{gr} = 0.025$. It was noted that progressively better match to the CT profiles was obtained as the injection rate was increased from an initial 0.1 cc/min to 4.5 cc/min through several steps. Using the parameters obtained, the simulated CO₂ saturation profiles during the imbibition cycle were found to be broadly comparable to the CT values.

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